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ORIGINAL ARTICLE

Optimal allocation of fault current limiters for sustaining overcurrent relays coordination in a power system with distributed generation

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Abstract This paper addresses the problem of overcurrent relays (OCRs) coordination in the presence of DGs. OCRs are optimally set to work in a coordinated manner to isolate faults with minimal impacts on customers. The penetration of DGs into the power system changes the fault current levels seen by the OCRs. This can deteriorate the coordinated operation of OCRs. Operation time difference between backup and main relays can be below the standard limit or even the backup OCR can incorrectly work before the main OCR. Though resetting of OCRs is tedious especially in large systems, it cannot alone restore the original coordinated operation in the presence of DGs. The paper investigates the optimal utilization of fault current limiters (FCLs) to maintain the directional OCRs coordinated operation without any need to OCRs resetting irrespective of DGs status. It is required to maintain the OCRs coordination at minimum cost of prospective FCLs. Hence, the FCLs location and sizing problem is formulated as a constrained multi-objective optimization problem. Multi-objective particle swarm optimization is adopted for solving the optimization problem to determine the optimal locations and sizes of FCLs. The proposed algorithm is applied to meshed and radial power systems at different DGs arrangements using different types of FCLs. Moreover, the OCRs coordination problem is studied when the system includes both directional and non-directional OCRs. Comparative analysis of results is provided.

1. Introduction

Integration of distributed generation (DG) can improve reliability, reduce power losses, improve power quality, decrease environmental pollution and diminish the need for network expansions. The protection devices are set to have a coordinated operation to isolate faults with minimum impact on customers. When DG units are connected to a distribution network, the magnitude and direction of fault current will be changed. So, the coordination between the network protection devices may vanish [1]. Autorecloser-fuse miscoordination and relay–relay miscoordination can occur. Size of DG, location of DG, and type of DG (static or rotating machine) influence the

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Nomenclature

A,B,C	relay characteristic constants
CTI	coordination time interval for backup-primary relay pair (in seconds)
i,j	relay indices
I_{fi}	ith relay near-end-fault current (in Amps).
$I_{fj,i}$	jth relay fault current for near-end fault at ith relay(in Amps)
I_{pi}	ith relay pickup current setting (in Amps)
$I_{pi\ \min}, I_{pi\ \min}$	lower and upper limits of I_{pi}
$I_{pi,Fixed}$	specific value of I_{pi}
J	sum of operation time of the primary relays (in seconds)
LDC	local distribution company
M_i	ith relay multiple of pickup current
$M_{j,i}$	jth relay multiple of pickup current for the ith relay near-end fault
N	total number of overcurrent relays in the system N
N_p	number of backup-primary OCR pairs
RCTI	revised coordination time interval for the backup-primary relay pair (in seconds)
t_i	operating time of the ith primary relay for near-end fault (in seconds)
$t_{j,i}$	operating time of the jth backup relay for near-end fault at the ith primary relay (in seconds)
Δt	operating time difference = $t_{j,i} - t_i$
TDS_i	time dial setting for the ith relay
$\mathrm{TDS}_{i\ \min}, \mathrm{TDS}_{i\ \max}$	lower and upper limits of TDS_i
FCL	fault current limiter
R-FCL	resistive fault current limiter
X-FCL	inductive fault current limiter
Z-FCL	resistive-inductive fault current limiter
$t_{B,bDG}$	operating time of backup relay before DG
$t_{M,bDG}$	operating time of main relay before DG
$t_{B,aDG}$	operating time of backup relay after DG
$t_{M,aDG}$	operating time of main relay after DG
R_i	resistance of the ith FCL
X_i	inductive reactance of the ith FCL
L	number of FCLs
$R_{\min}$, and $R_{\max}$	lower and upper limits of FCL resistance
$X_{\min}$, and $X_{\max}$	lower and upper limits of FCL inductive reactance

share of DG in total fault current. Thus, these factors determine the DG effect on protection system coordination [2]. Directional overcurrent relays (DOCR) form the primary protection of distribution and sub-transmission systems and the secondary protection of transmission systems. The overcurrent relay (OCR) coordination is realized by adjusting the pickup current setting (I_p) and the time dial setting (TDS) of OCR for increasing the selectivity and reliability of protective system [3]. Setting of OCRs is difficult, especially in the multi-loop, multi-source networks. Trial and error, topological analysis, and optimization methods are used for OCRs setting [4].

The possible solutions to the OCR miscoordination problem in power delivery system (PDS) with and without DGs are searched. In case of PDS without DG, the authors in [5] reported an approach to break all system loops and coordinate the breakpoint for both directions. In [6,7], a linear graph theory method was used to determine a set of breakpoints. Furthermore, optimization approaches such as dual simplex [8,9] and genetic algorithms [10] were used to minimize the relay operating times. To provide coordination between OCRs under the presence of DG, various techniques are proposed [4]. Ref. [11] discussed the high-impedance protection applications for tripping acceleration. But this method depends on current transformer (CT) whose dynamic behavior influences the protection stability. Ref. [12] proposes utilizing the distribution automation system capabilities for protection coordination. One drawback of this method is that the number of protection zones increases when the number of DGs increases. So, many isolating circuit breakers will be needed and the scheme may not be economic. Communication-assisted digital relay approach is presented in [13] to achieve coordinated operation of OCRs. Complexity and enlarged failure rates are major concerns in this method. Ref. [14] reviews the protection schemes and coordination techniques in microgrid systems. A neural network and backtracking-based protection coordination scheme for distribution system with DG is presented in [15].

One approach to control fault current in the presence of DG is the use of Fault Current Limiter (FCL) [16]. FCL basically provides nearly zero impedance in normal operation without energy loss or voltage drop. If a fault occurs, the FCL will insert high impedance within few milliseconds. This reduces the fault currents to lower levels within circuit breakers capabilities [16]. FCLs can be divided into three main categories [17]: passive FCLs, solid-state FCLs, and hybrid FCLs. The passive FCL simply inserts a current-limiting inductance without external control signals. The solid-state FCL is formed by power electronics equipment and sensors. The hybrid FCLs use combination of mechanical switches, solid-state devices, superconducting elements and other technologies to mitigate fault current [17]. FCLs are generally sophisticated and expensive equipment. The FCL size is defined as the impedance value it introduces under fault conditions. FCL cost typically increases when its size increases. Placement and sizing of FCLs in a PDS greatly determine its impact on protection system. In [18], genetic algorithm-based method was implemented to determine the optimal number and locations of FCLs in a radial distribution system with DG to minimize the total cost of protective devices. In [19], the optimal FCLs sizes in a distribution system with DG are determined. Nonetheless, the FCLs locations are hypothetically assumed and their cost is not considered. In [20], FCLs are utilized to restore DOCRs coordination in the presence of DG. So, the optimal OCRs settings without DG are maintained with DG. This avoids any need to OCRs resetting. The latter is a tedious task especially in a large scale PDS. Besides, it may not be adequate to keep OCRs coordination in the presence of DG. However, sizes and locations of FCLs are estimated by trial and error in [20] and cannot be optimal from performance and cost perspectives.